NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2951

FLIGHT INVESTIGATION OF THE EFFECT OF TRANSIENT WING RESPONSE ON WING STRAINS OF A FOUR-ENGINE BOMBER AIRPLANE IN ROUGH AIR

By Harold N. Murrow and Chester B. Payne

Langley Aeronautical Laboratory
Langley Field, Va.

Washington
June 1953

1D

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2951

FLIGHT INVESTIGATION OF THE EFFECT OF TRANSIENT WING RESPONSE ON WING STRAINS OF A FOUR-ENGINE BOMBER AIRPLANE IN ROUGH AIR

By Harold N. Murrow and Chester B. Payne

SUMMARY

A flight investigation was made on a four-engine bomber airplane to determine effects of wing flexibility on wing strains developed in flight through clear-air turbulence. The amplification of strain due to flexibility effects was determined by comparing the strains for a unit normal acceleration that are developed when the airplane experiences a gust with the strains for a unit normal acceleration that are developed in a pull-up. At a station near the root the bending strains due to gusts were on the average 31 percent greater than the corresponding pull-up strains. The amplification was found to vary with spanwise location, diminishing slightly at successive outboard stations except at the most outboard station where it increased.

Variations from 180 to 250 mph in the airspeed and from 91,000 to 103,000 pounds in weight had no pronounced effect on the amplification factor. The amplification was found to be a function of gust-gradient distance (as measured by the time interval to pass from the 1g level-flight condition to peak acceleration), decreasing as the gradient distance increased. The shear-strain time histories resembled the bending-strain histories at outboard stations, and approximately the same amplification factors were found for shear strains as for bending strains at these stations.

Some supplementary calculation studies of the amplification factor as a function of gradient distance gave results which roughly substantiate the results found from the flight tests.

INTRODUCTION

A series of flight investigations has been made in rough air with a two-engine transport airplane and a four-engine bomber airplane to obtain

a practical measure of how wing strains and accelerations induced by gusts are amplified by transient-response effects associated with wing flexibility. Some results of these investigations have been reported in references 1, 2, and 3. Reference 1 deals with the acceleration results for the twin-engine transport and indicates that the peak accelerations at the fuselage were on the average 20 percent greater than the peak accelerations at the nodal points of the fundamental mode, the latter being used as measure of over-all airplane acceleration; reference 2 deals with strain measurements on this transport and indicates that the peak bending strains were also increased about 20 percent by flexibility effects. Reference 3 reports the acceleration measurements on the four-engine bomber and shows that for this airplane the peak fuselage accelerations were about 28 percent greater than the nodal accelerations.

The purpose of the present paper is to present the results of strain measurements made on the four-engine bomber airplane. In the flight investigation, accelerations and strains were measured at a number of spanwise stations during flights through clear-air turbulence. In addition, wing-twist measurements were made to determine the extent to which torsional effects were present. The effects of forward speed and fuel load distribution were also investigated. The amplification in strains due to the transient response characteristics was determined in the same manner as was done for the twin-engine airplane; that is, the wing strains for a unit normal acceleration of the airplane under the action of gusts were compared with the strain that is developed for a unit normal acceleration during a pull-up. A few computed results are also compared with the experimental results.

APPARATUS AND TESTS

The characteristics of the test airplane are given in table I, and a three-view line drawing, in figure 1. The spanwise stiffness distribution is shown in figure 2 and the estimated spanwise weight distribution, exclusive of fuel, is shown in figure 3(a). The limits of the average fuel load distribution of all test runs for the wing-heavy and wing-light conditions are shown in figures 3(b) and 3(c), respectively.

Electrical wire-resistance strain gages connected as four active gages in a bridge circuit were installed on the wing spars at the spanwise stations (measured from the airplane center line) indicated in figure 4. These gages were mounted on each spar as illustrated by the sketch in figure 4; the gages mounted along the spar flanges were used to measure bending moment, whereas the gages mounted in a V-arrangement were used to measure shear (mounting of the gages on both sides of the spar web was not feasible).

Calibrating loads were applied to the wing at a number of chordwise and spanwise positions and the results showed that the strain indications were a linear function of load for all loading positions. Since the number of recording channels was limited, the outputs of all the strain gages could not be recorded separately. The outputs of the strain-gage installations for the front and rear spars of stations 432 and 590 on the left wing were therefore combined to give a single output for each station. In order to obtain strain measurements at stations 432 and 590 that would be independent of chordwise loading, the strain ratio between the front and rear spars for various chordwise loadings had to be obtained. After these loadings were obtained, the gages were combined electrically in a ratio that would be independent of chordwise loading. All strain indications were recorded on a multichannel oscillograph.

An average acceleration measurement was obtained by electrically combining the outputs of two accelerometers mounted near the elastic axis, one at station 278 on the right wing and one at station 278 on the left wing (the estimated nodal points of the fundamental bending mode). A standard NACA airspeed-altitude recorder was used to obtain the record of airspeed and altitude. Recording gyroscopes (NACA attitude-pitch recorders) were located at the stations shown in figure 4 to obtain a measure of the twist of the wing with reference to the fuselage center line. All recorders were correlated by means of a NACA 1/2-second chronometric timer.

The tests were conducted over a course approximately 50 miles in length. Two flights were made at each of two weight conditions, averaging 91,000 and 103,000 pounds, respectively, and four runs were made during each flight, two at a forward speed of 250 mph and two at 180 mph, giving a total of 16 runs for the entire series. The different weight conditions are due entirely to variation in fuel load (see fig. 3), and the flights were designated as "wing heavy" and "wing light" according to the weight of fuel on board. Slow pull-ups were made immediately before and after the rough-air runs to obtain data for use as a quasi-static reference condition. These pull-ups were made at the test speeds of the runs and at higher altitudes where smooth-air conditions were found.

BASIS OF ANALYSIS OF DATA

The amplification of strain due to flexibility effects is normally defined as the ratio of the deformation under dynamic action to the deformation caused by the same load applied statically. Since these static reference strains cannot be obtained in flights through gusts, the strains imposed on the structure in pull-ups made sufficiently slow to eliminate dynamic response were used. In utilizing a pull-up as the reference condition, quasi-static elastic twists and other aerodynamic features of the

airplane which are also present in rough air are taken into account. However, although the angle-of-attack distribution along the span is roughly uniform for the pull-up condition, it is not necessarily so in rough air.

The actual method used for treating the strain data is to form the ratio of the wing strain in a gust to the wing strain caused by a 1g pull-up and to plot this ratio against the nodal acceleration. The slope of the line through the data is herein defined as the amplification factor. A 1:1 slope (amplification factor of 1.0) would indicate the same relations for gusts as for pull-ups, that is, no dynamic response.

Considering the assumptions implied in using the wing strain in pull-ups as a reference, it is apparent that the amplification of strains so obtained includes effects not normally considered in dynamic-response calculations. Some of these effects were pointed out in reference 2. Among these effects are the influence of ailerons, the nonuniform distribution of gust velocity across the span, and unsymmetrical conditions of vibration and airplane motion that may cause scatter in the data. Some of these factors tend to increase and others tend to decrease the amplification, so that the net result is a large amount of scatter in the data that will increase the difficulty of obtaining agreement between calculation and experiment.

ACCURACY OF THE RESULTS

The instrumentation and character of the records were such that the accuracy of the individual measurements was estimated to be as follows:

Strain indications, percent	±5
Accelerations, g units	±0.05
Wing twist, deg	±0.10

The strain measurements in pull-ups and in the laboratory load calibrations were linear within the accuracy of the measurements (it was not known whether web buckling occurred and affected the spar-web measurements). Variations of airspeed, altitude, and weight from the prescribed test conditions were not sufficiently large to alter the results.

RESULTS AND DISCUSSION

Bending strains.- Time histories of strain indication and nodal-point acceleration for a pull-up and a portion of a gust record are shown in figures 5(a) and 5(b), respectively. Since the outputs of the gages for

the front and rear spars at the two outboard stations were combined, their strains are designated by spanwise location only. The nodal-acceleration and bending-strain records in figure 5(a) show no evidence of superimposed structural vibrations except those of high frequency caused by engine vibration. The pull-ups were made slowly enough (approximately 3 seconds were taken to reach peak load) to approximate pseudo-static loading so that it seems reasonable to assume that the effects of dynamic flexibility were negligible in pull-ups.

The time histories for flight through gusts (fig. 5(b)) show a predominant vibratory strain with a frequency of approximately 3 cps which is attributed to the superposition of the wing fundamental mode on gust strains. The time history also shows that the vibratory oscillations of 3 cps were in phase for the front- and rear-spar locations and for corresponding stations on the left and right wings. In addition to the fundamental bending mode, figure 5(b) also shows some evidence of higher mode contributions at frequencies of 5 and 7 cps. Although the presence of these higher modes can be detected at all the measuring stations, they are most predominant at the outboard stations and especially at the most outboard station (station 590). The time history of the nodal acceleration in the figure shows no evidence of the fundamental mode but does indicate vibratory structural accelerations having a frequency of about 5 cps. On the whole, the bending-strain histories closely follow the pattern shown by the nodal accelerations.

In order to obtain reference strains for the weight condition of each rough-air run, the strain indications per g in pull-ups were plotted against the various weights from the different flights as shown in figure 6 for the wing-heavy condition. The data of this figure cover the complete weight range since the pull-ups included in the figure were made at the beginning and end of each flight. Figure 6 is used by selecting the weight condition for a particular run and reading the corresponding reference strain per g from the curve.

When the bending-strain measurements for the front and rear spars at stations 432 and 590 were combined, the dynamic-response effects for the front and rear spars were assumed to be the same at these stations, as indicated in reference 2. To prove that the relation (evident in the time histories) between the front- and rear-spar strains was the same for gust and pull-up conditions, the ratio of the wing strains in gusts to the wing strains per g in a pull-up for the front spar were plotted against those for the rear spar for the stations where separate measurements were made for front and rear spars. The data for station 126 are shown in figure 7 and the 1:1 relationship verifies the previous assumption. Considering these results for the most inboard station and the lack of any forwardly located masses at the outboard stations, it seems reasonable to assume that the dynamic-response effects on the bending strains would be the same for the front and rear spars at stations 432

and 590. In fact, the relationship between the strains for the front and rear spars would be expected to be much better than that shown in figure 7, since data for the next outboard station (station 255) showed even less scatter than that shown for station 126. The bending strains in the front and rear spars at any station therefore appear to have the same relation to each other in gusts and in slow pull-ups.

Questions have arisen as to the effect of torsion or wing twist on wing bending and shear strains. A time history of one of the most severe conditions of wing twist during the rough-air flights and the corresponding time history of the estimated angle of attack is shown in figure 8. This figure shows that the wing twist is primarily vibratory in nature and very small in magnitude compared to the angle-of-attack change; therefore, twist seems to have a negligible effect and is so assumed hereinafter.

For each of the runs in rough air, a number of peak incremental strains from the 1g reference and the associated nodal-acceleration increments were selected to represent the data. The selected acceleration peaks were evaluated from the average nodal acceleration (combined left and right nodal accelerometers) by fairing out the engine vibrations and all modes higher than the first.

Data from all runs of each particular condition were treated as one group of data, and a typical plot is shown in figure 9, which is for station 126. For a given nodal acceleration, the bending-strain indications in gusts are seen to be greater, on the average, than the corresponding pull-up strain, and, although appreciable scatter is evident, the trend of the data is roughly linear. The dashed line passes through the origin and a point which is established as the average absolute value of both the ordinate and abscissa of the data. The slope of this line, in this case 1.31, is taken as the estimated mean amplification factor of the strain due to wing dynamic response in gusts.

The amplification factors obtained for each measuring station and the four different combinations of speed and weight are shown in table II(a). Although there is a tendency for the values to be slightly higher for the low-speed and the wing-heavy conditions, the differences are within the accuracy of the results and therefore it would seem that no definite conclusions can be drawn from these results as far as weight and speed are concerned.

In order to study the weight and speed effect further, the dynamic response for the test airplane was calculated by the method of reference 4 for a sharp-edge gust for the different conditions of speed and weight. This method is based on the response of an airplane due to a gust where the degrees of freedom of vertical motion and wing bending are included. The calculated bending-moment response factors (ratio of

the maximum root bending moment obtained for the flexible airplane to the maximum bending moment that is obtained when the airplane is considered rigid) that were obtained for this sharp-edge-gust encounter are:

Wing-heavy low-speed condition	1.62
Wing-heavy high-speed condition	1.52
Wing-light low-speed condition	1.57
Wing-light high-speed condition	1.44

The values indicate slightly higher amplification factors for the wing-heavy and the low-speed conditions and serve to confirm the trends suggested by the experimental data. A similar trend to these calculated sharp-edge-gust results would also be found for graded gusts having a finite distance to peak gust velocity.

The average amplification factor for each condition at each measuring station in table II(b) shows that the highest bending amplification factor was obtained at the most inboard measuring station (station 126), with the values decreasing in the outboard direction except for the most outboard station (station 590).

Amplification factors for the wing-heavy high-speed condition were calculated by the method of reference 4. The calculations were made for a sharp-edge gust and sine-type gusts with distances to peak gust of 5 and 10 chords and are shown in figure 10 together with the corresponding flight-test values. The results calculated by the method of reference 4 do not reflect the effects of higher modes, since the calculations are restricted to the fundamental mode of vibration. Also shown in figure 10 is a plot of the amplification factors for a sharp-edge gust calculated by the method of reference 5 in which higher modes of vibration (at least 3), as well as the fundamental, are inherently included in the calculations. Comparison of the two sharp-edge-gust calculations shows that the inclusion of higher modes resulted in higher amplification factors at the outboard stations. Further inspection of figure 10 indicates that at the two inboard stations the amplification factors for the flight data correspond to those calculated for a sine gust with a distance to peak gust of approximately 5 chords. At the outboard stations, however, the amplification factors found in the tests showed the same trend as the amplification factors calculated for a sharp-edge gust where higher modes are considered. The large amplification factor obtained for station 590 (shown in table II(b)) is therefore attributed in part to the higher modes. This result is in accord with the observation made in the earlier discussion of figure 5(b) that the higher mode effects were more prominent at the outboard stations than at the inboard stations.

Calculations have shown that dynamic response depends on gust-gradient distance. In order to see whether this dependence is also evident

in the flight results, data for each flight condition and measuring station were sorted on the basis of time to reach peak acceleration (time of load application from the 1g level to peak acceleration). Data were sorted according to values of time to reach peak acceleration and divided into groups of 0.1-second intervals of time to reach peak acceleration. Then for each group of data the average amplification factor was determined; these factors for station 126 are shown in figure 11. It may be seen that the amplification factors are significantly greater when the time to reach peak acceleration is small. Calculated results (by the method of ref. 4) also shown in this figure indicate the same general trend, although the calculated results decrease faster with increasing values of the abscissa. Repeated gust effects, aileron motions, higher modes of vibration, and nonuniform distribution of gust velocity across the wing span in flight, as well as the method by which the records were read, may account for the differences in the test data and the calculations, or at least for a substantial portion.

Shear strains.- Inspection of the time histories of the strains associated with shear and the nodal-point acceleration in a slow pull-up in figure 5(a) shows that the rear-spar-web strains at station 126 for both wings change very little during the pull-up; therefore, the rear-spar web during this particular maneuver carries very little shear load at this station. Further inspection of figure 5(a) indicates that all the shear strains increase positively with positive nodal acceleration except for the front-spar web at station 126. In this case the strain variation is in the negative direction and is probably due to torsional effects caused by forwardly located engine nacelles at this station. As was the case for the bending strains, no dynamic effects seem to be present in the shear strains for the pull-up condition.

Inspection of figure 5(b) shows that the vibratory strains are very prominent in the time histories for flight in gusts. The predominant frequencies appear to be those associated with the fundamental mode of vibration, approximately 3 cps, and higher modes of 5 and 7 cps. In the case of the two most inboard stations (stations 126 and 255), the vibratory strains are predominant and little or no direct gust strains appear to be present. The same result was also found in reference 2 for the shear strains. For this reason, no evaluation of amplification factors was attempted at these stations. At the two outboard stations, stations 432 and 590, where the shear-strain measurements for the front and rear spars were combined as a single recording, the time histories show the same general characteristics as the time history of the nodal-point acceleration. Figure 5(b) shows that the shear-strain traces for the two outboard stations, stations 432 and 590, for flights in rough air have the same characteristics as the bending strains; therefore, the shear strains due to gusts at the two outboard stations are much more predominant than those due to vibrations. It would seem, therefore, that for stations 432 and 590 where there is an absence of forwardly located masses and relatively low wing mass, the relationship between the front- and rear-spar-web strains in gusts would be expected to be approximately the same as

that found in pull-ups; this result is in conformity with results found in reference 2. The average amplification factors found for the shear or spar-web indications and shown in table II(b) are 1.17 for station 432 and 1.21 for station 590 and agree closely with those obtained for bending-strain indications.

CONCLUSIONS

Strain measurements made on a four-engine bomber airplane in rough air were compared with measurements made in slow pull-ups which were considered as a simulated rigid-body reference condition. Analysis of the results indicates that for the airplane tested:

1. Wing bending flexibility caused the bending strain at a station located inboard to be on the average of 1.31 times as great as what the strains would be if the airplane behaved as a rigid body. The amplification factor decreased with each successive outboard station and then increased slightly at the tip station.

2. The bending strains in the front and rear spars at any station showed the same relation to each other in gusts and in slow pull-ups.

3. No pronounced effect in the amplification factors for bending strains was observed for a change in weight from 91,000 to 103,000 pounds or a change in airspeed from 180 to 250 mph.

4. The amplification factor appears to be a function of gradient distance and was found to decrease as the time to reach peak acceleration increased. Some calculation studies roughly substantiated the trend found experimentally.

5. At the inboard stations spar shear strains were predominantly of a vibratory nature, and no amplification factors could be determined for these stations. At the outboard stations, where the wing mass is relatively low, the shear-strain time histories resembled the bending-strain histories and the amplification factors for the shear or spar web are in close agreement with those for the bending strains.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 6, 1953.

REFERENCES

1. Shufflebarger, C. C., and Mickleboro, Harry C.: Flight Investigation of the Effect of Transient Wing Response on Measured Accelerations of a Modern Transport Airplane in Rough Air. NACA TN 2150, 1950.

2. Mickleboro, Harry C., and Shufflebarger, C. C.: Flight Investigation of the Effect of Transient Wing Response on Wing Strains of a Twin-Engine Transport Airplane in Rough Air. NACA TN 2424, 1951.

3. Mickleboro, Harry C., Fahrer, Richard B., and Shufflebarger, C. C.: Flight Investigation of Transient Wing Response on a Four-Engine Bomber Airplane in Rough Air With Respect to Center-of-Gravity Accelerations. NACA TN 2780, 1952.

4. Houbolt, John C., and Kordes, Eldon E.: Gust-Response Analysis of an Airplane Including Wing Bending Flexibility. NACA TN 2763, 1952.

5. Houbolt, John C.: A Recurrence Matrix Solution for the Dynamic Response of Aircraft in Gusts. NACA Rep. 1010, 1951. (Supersedes NACA TN 2060.)

TABLE I

CHARACTERISTICS OF TEST AIRPLANE

Span, ft	141.2
Mean aerodynamic chord, ft	12.9
Wing area, sq ft	1,739
Lift-curve slope per radian	5.04
Aspect ratio	11.6
Center-of-gravity position, approximate percent mean aerodynamic chord	22
Fundamental frequency, wing bending (ground vibration tests, no-fuel condition), cps	3.3
Estimated fundamental wing frequency from flight records, wing-heavy condition, cps	2.8
Estimated fundamental wing frequency from flight records, wing-light condition, cps	3.0
Vibrations due to higher modes, cps	6.0

TABLE II

AMPLIFICATION FACTORS

(a) Individual amplification factors

Condition	Station 126				Station 255		Station 432	Station 590	Station 432	Station 590
	RFB*	RRB*	LFB*	LRB*	LFB*	LRB*	LB*	LB*	LS*	LS*
Wing light, high speed	1.28	1.25	1.30	1.28	1.23	**1.15	**1.09	1.28	1.17	1.19
Wing light, low speed	1.31	1.27	1.33	1.29	1.28	**1.21	**1.15	1.31	1.16	1.20
Wing heavy, high speed	1.32	1.31	1.33	1.30	1.22	1.21	1.15	1.20	1.18	1.19
Wing heavy, low speed	1.37	1.26	1.35	1.37	1.29	1.28	1.18	1.29	1.23	1.28

(b) Average amplification factors

Station	Bending amplification factor	Shear amplification factor
126	1.31	----
255	1.23	----
432	1.14	1.17
590	1.27	1.21
Average	1.24	1.19

*RFB right front bending
RRB right rear bending
LFB left front bending
LRB left rear bending
LB left bending (front and rear spars combined)
LS left shear (front and rear spars combined)
** Two runs only.

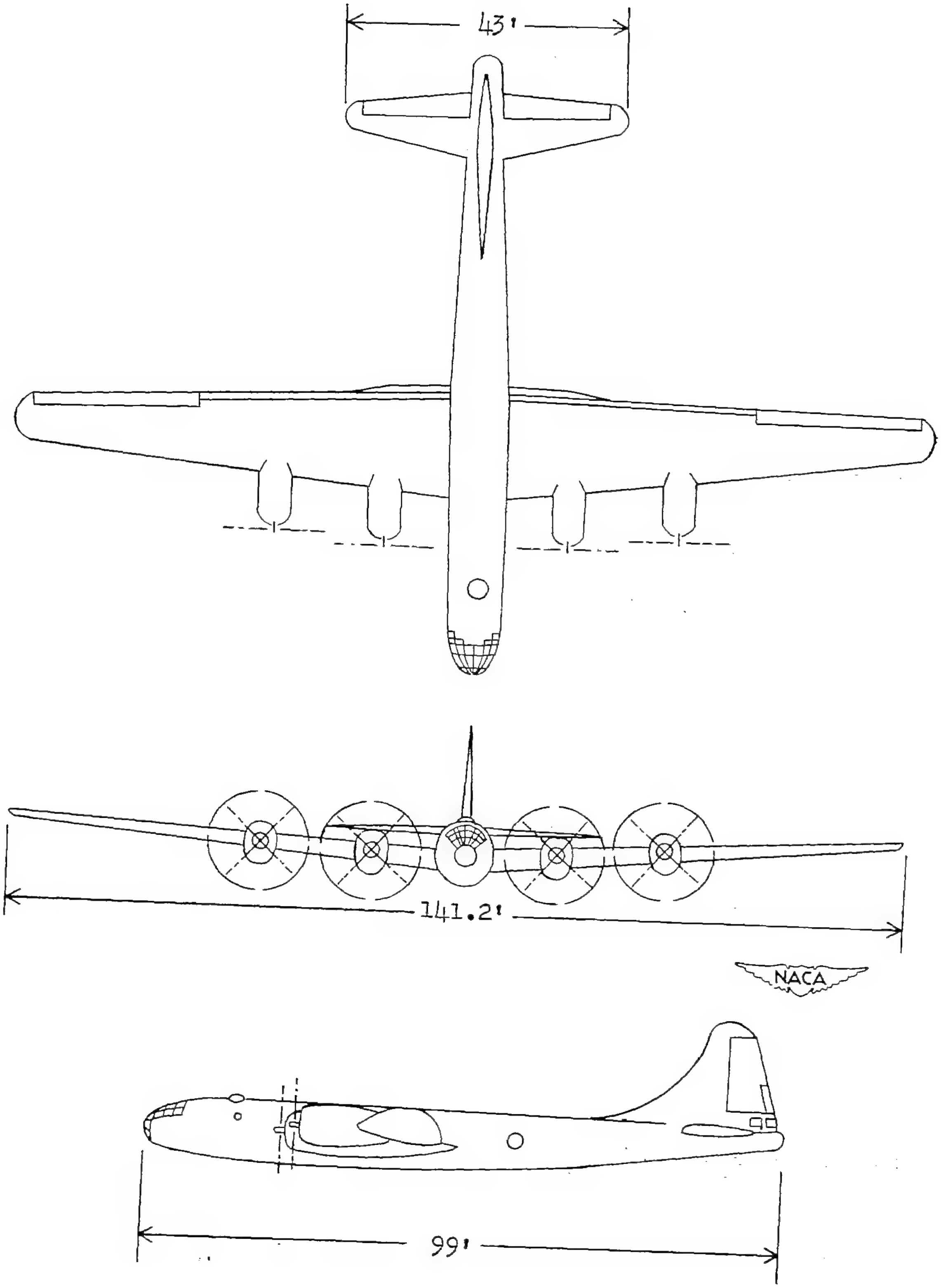


Figure 1.- Three-view drawing of test airplane.

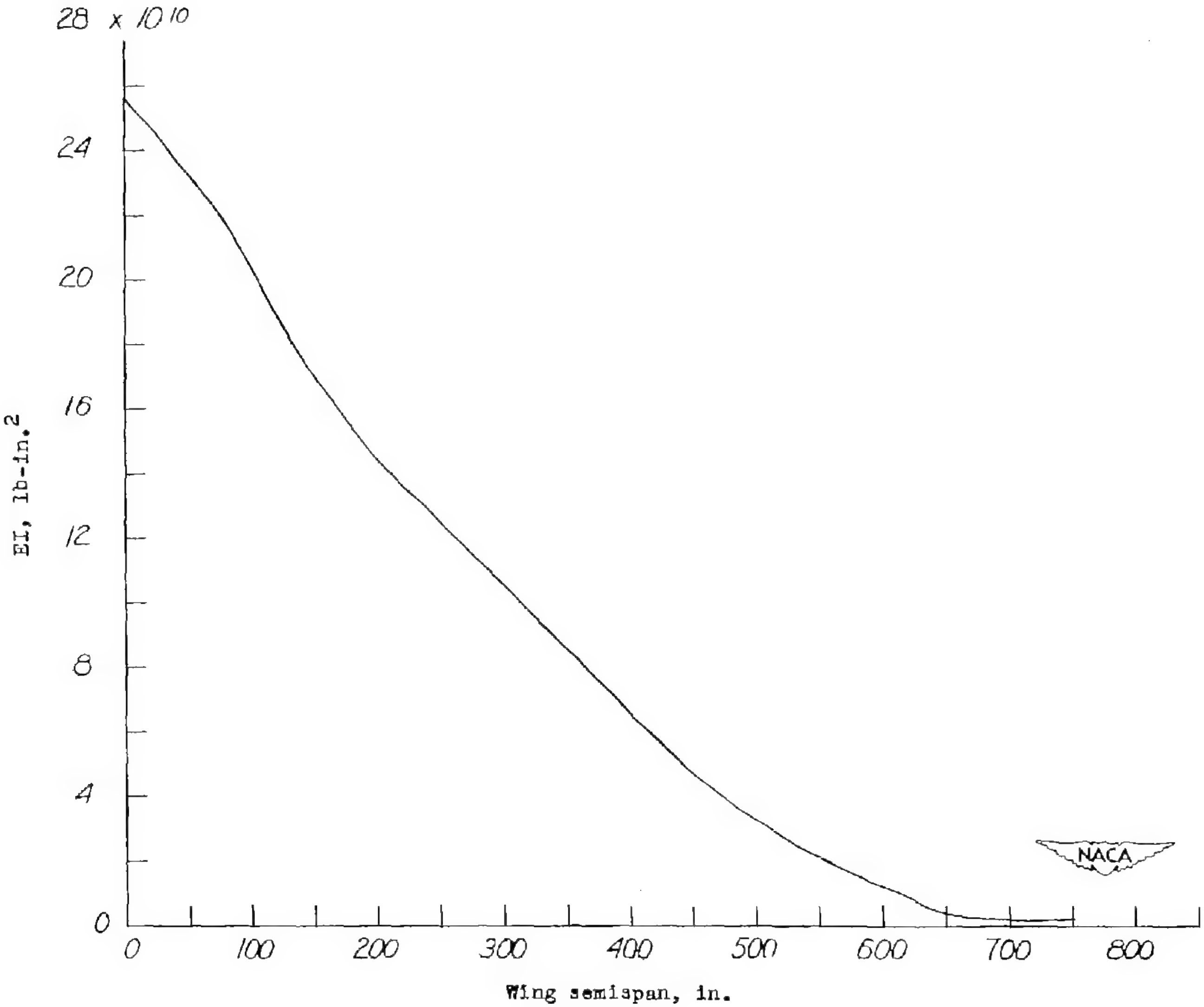
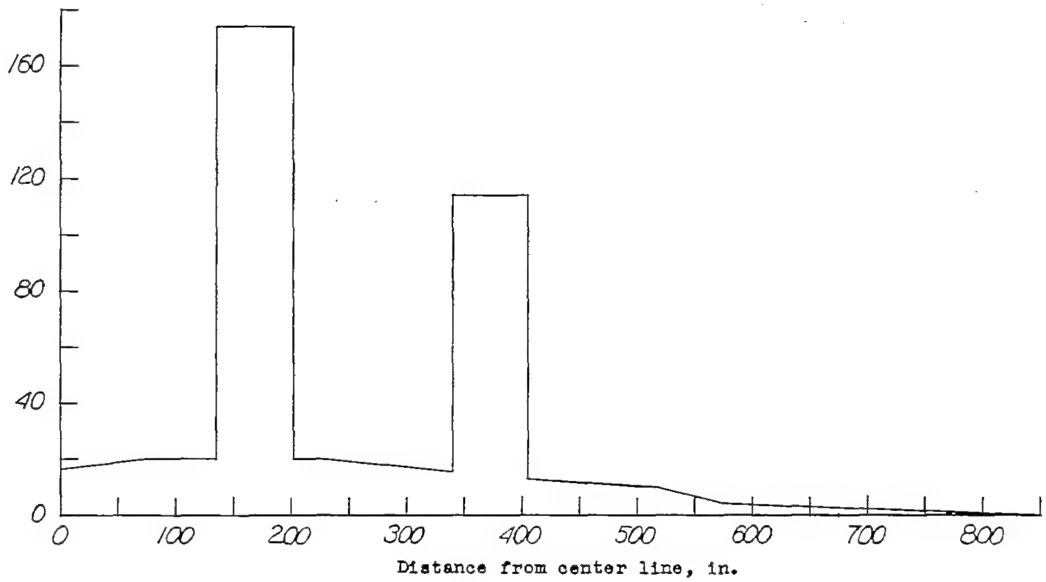
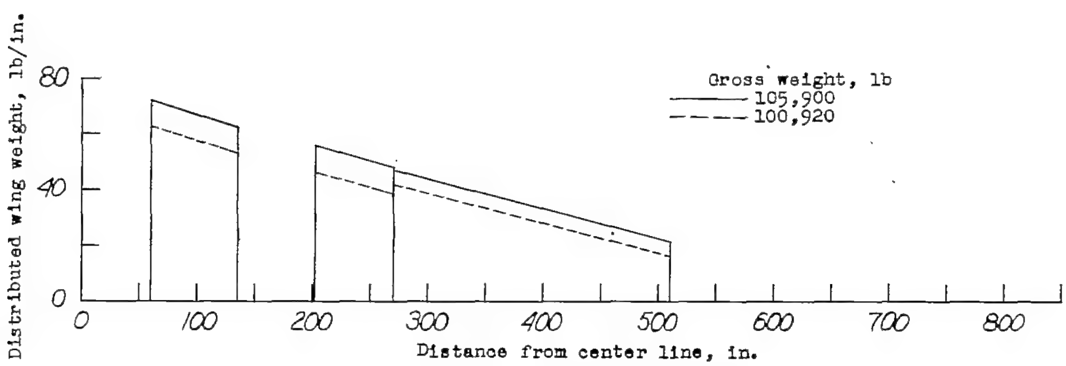


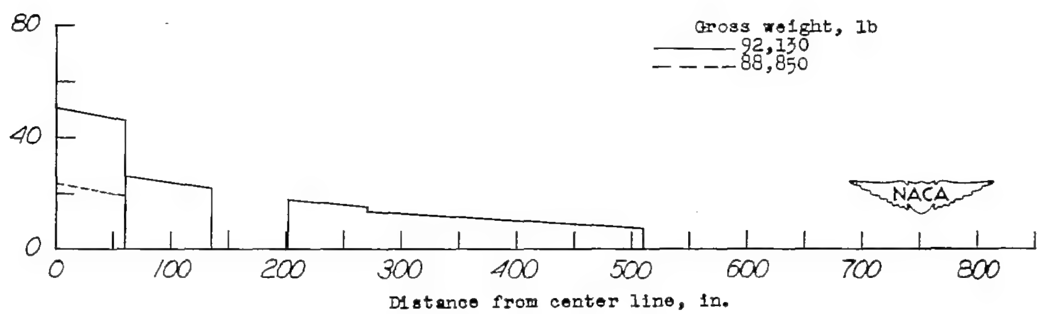
Figure 2.- Estimated spanwise stiffness distribution.



(a) Wing structure and nacelles.



(b) Fuel load, wing-heavy condition.



(c) Fuel load, wing-light condition.

Figure 3.- Estimated spanwise wing weight distribution.

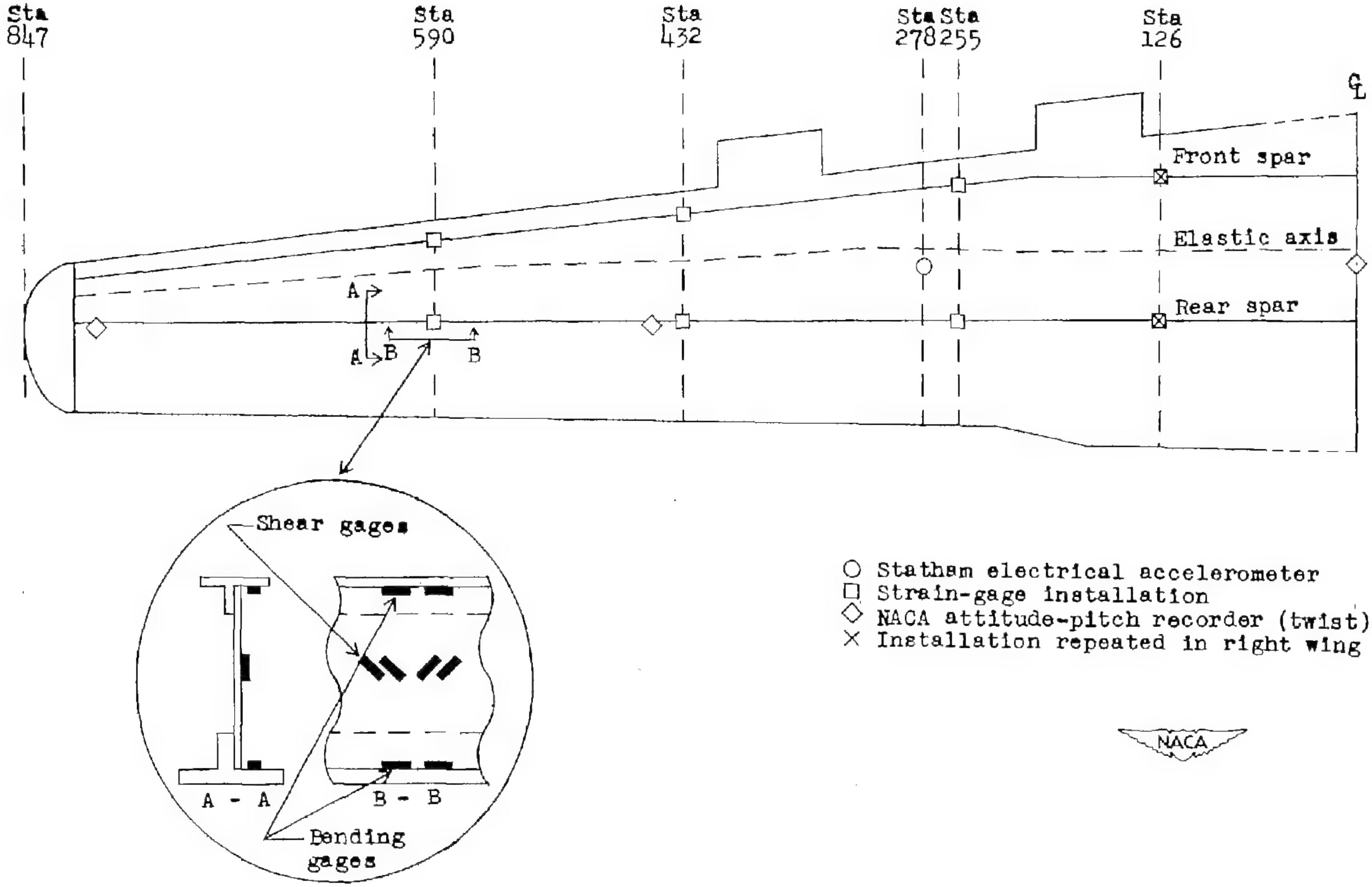
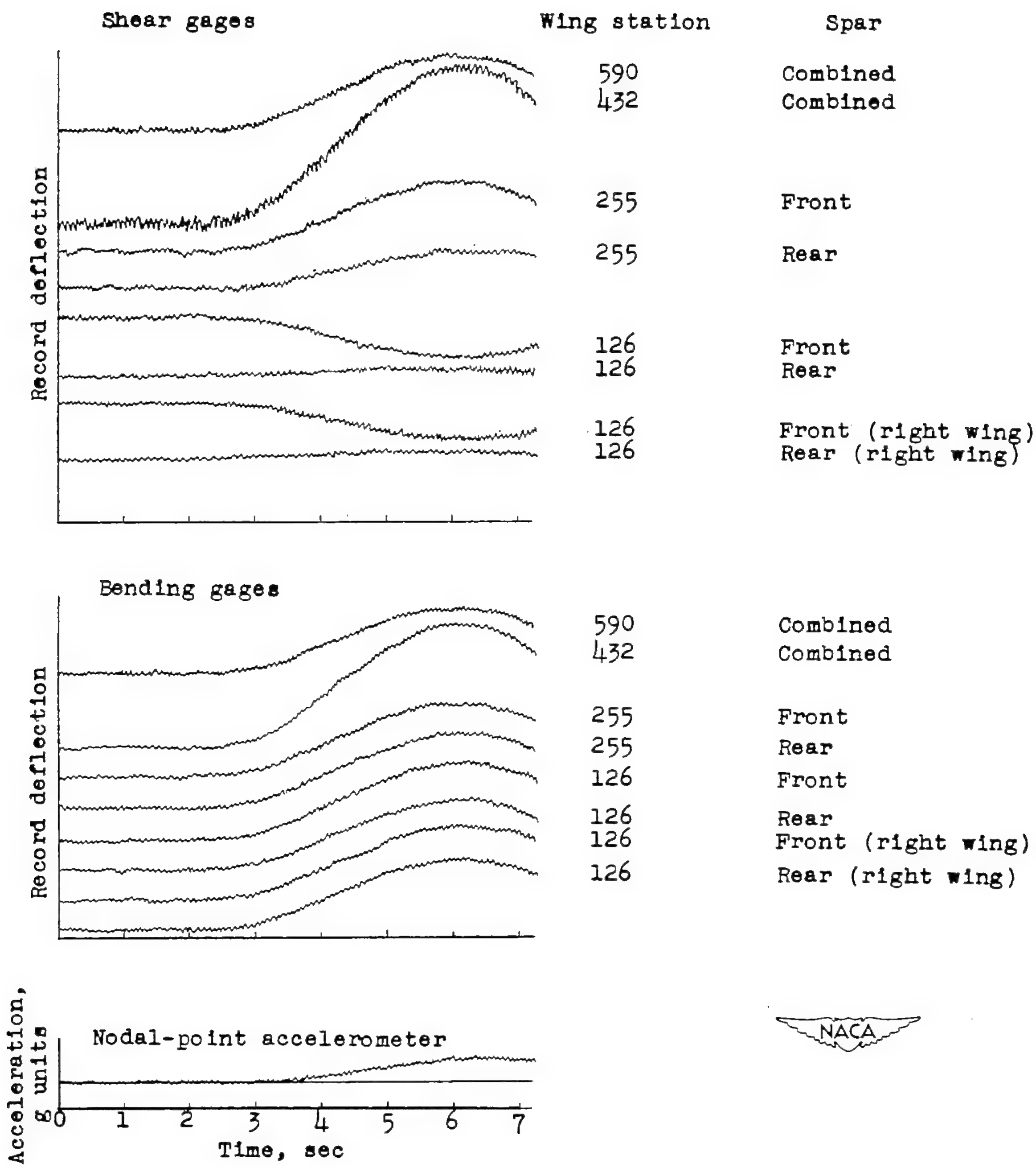
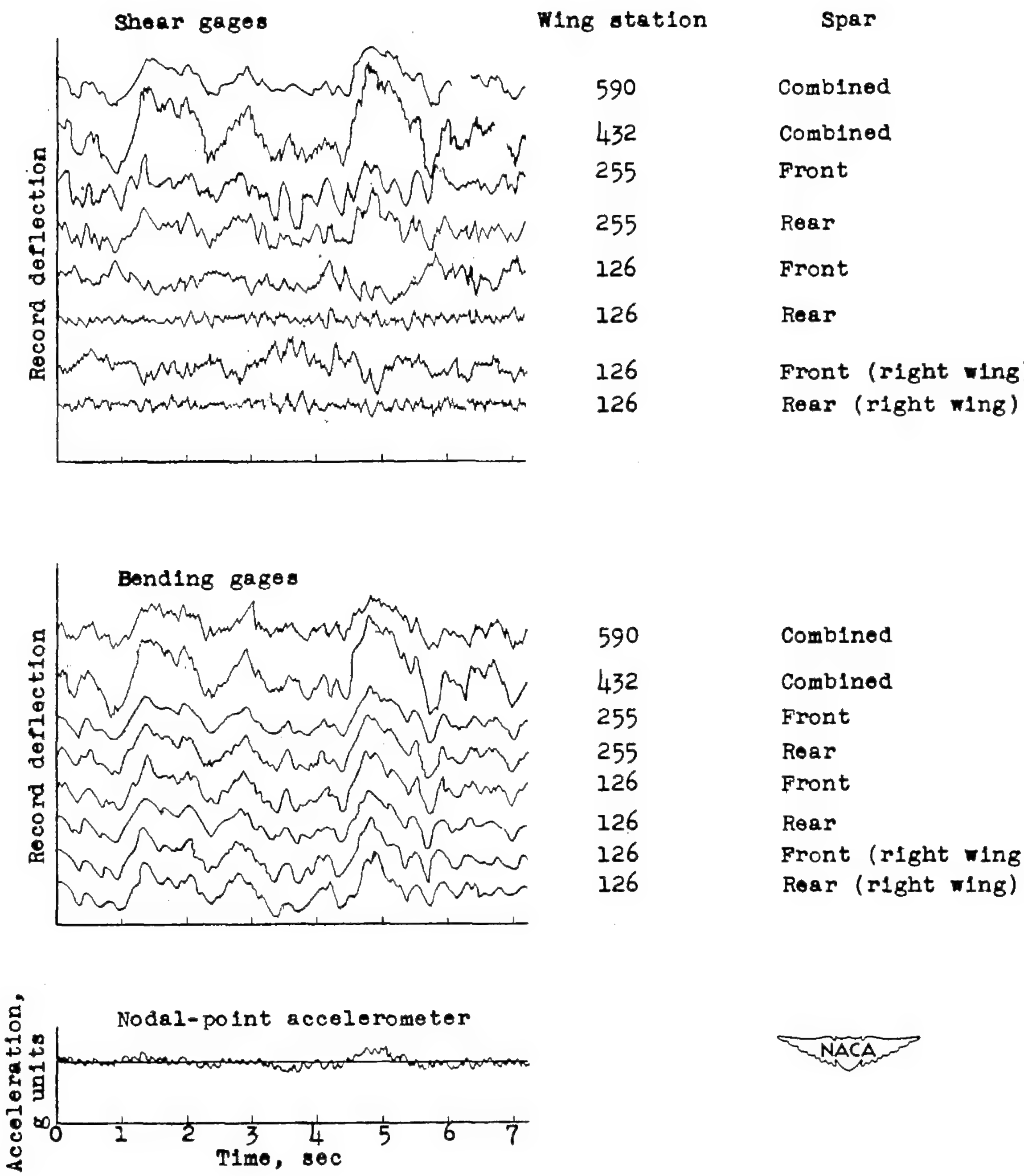


Figure 4.- Location of acceleration and strain-gage installations and NACA attitude-pitch recorders (twist) in left wing of test airplane.



(a) Pull-up record.

Figure 5.- Time histories of wing-strain indication and nodal-point acceleration. (Stations are for left wing unless otherwise noted.)



(b) Portion of gust record.

Figure 5.- Concluded.

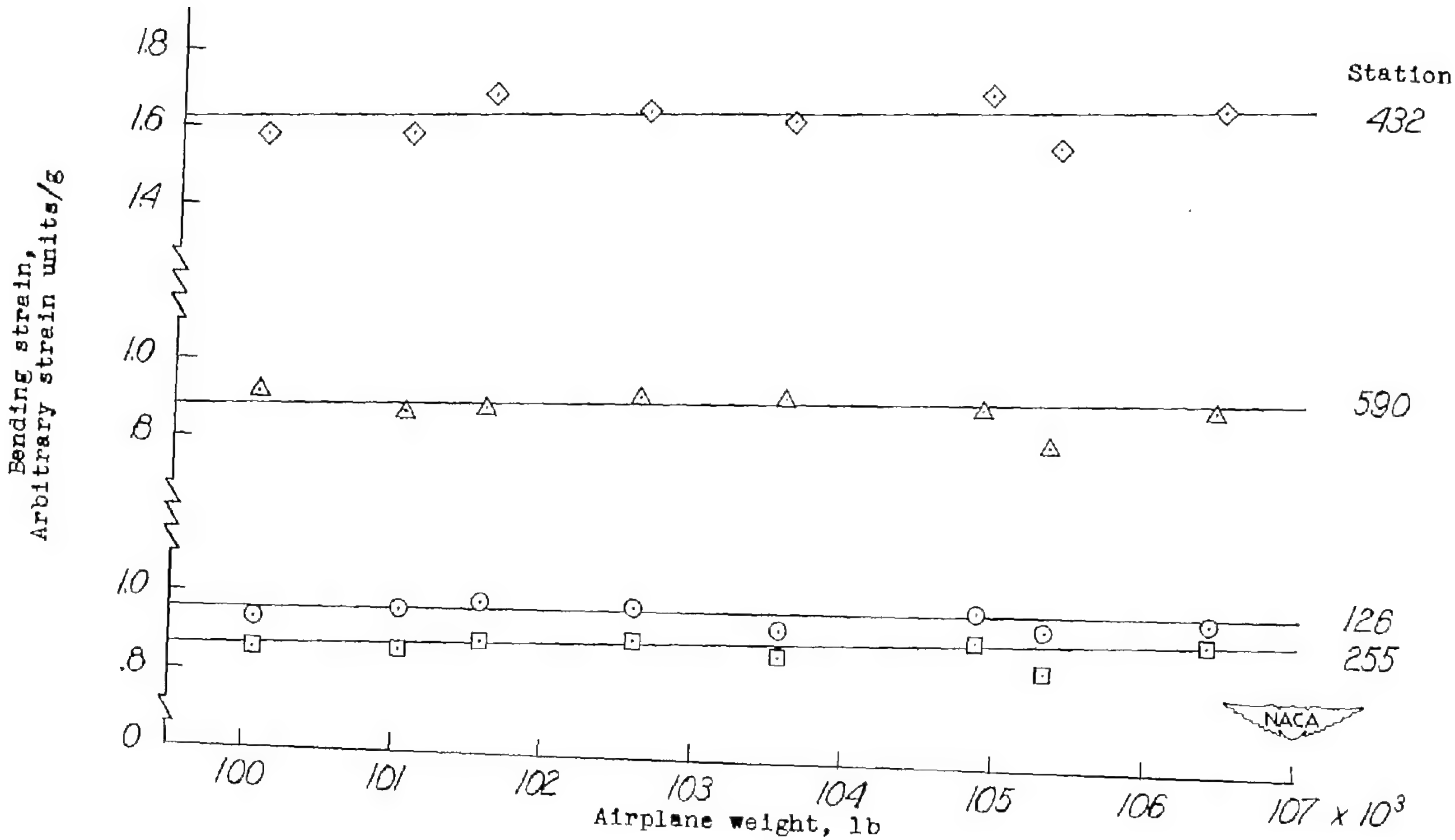


Figure 6.- Variation of bending strains in pull-ups with airplane weight for wing-heavy high-speed condition. Left wing; front spar.

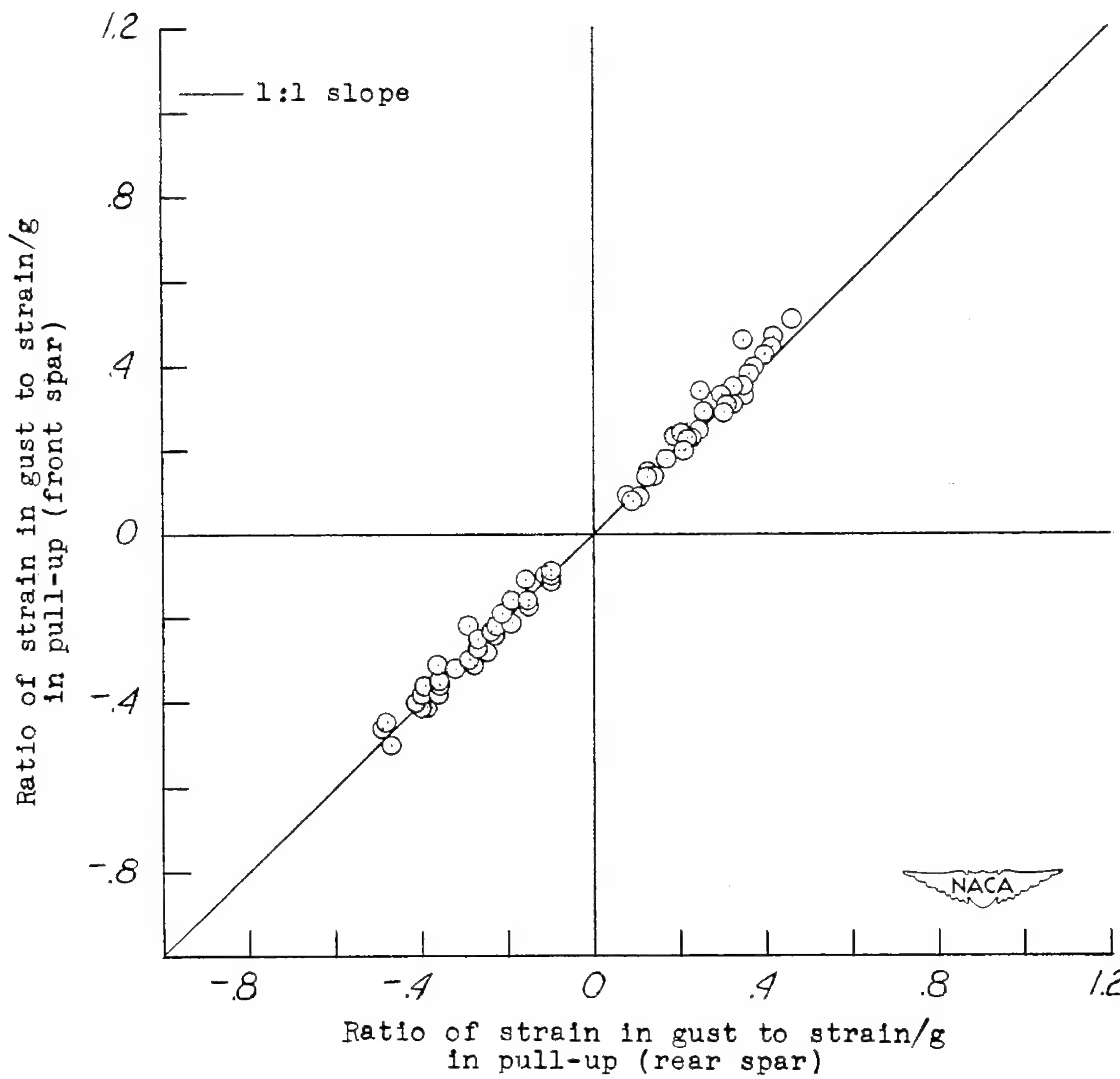


Figure 7.- Variation of front-spar bending strain with rear-spar bending strain. Station 126.

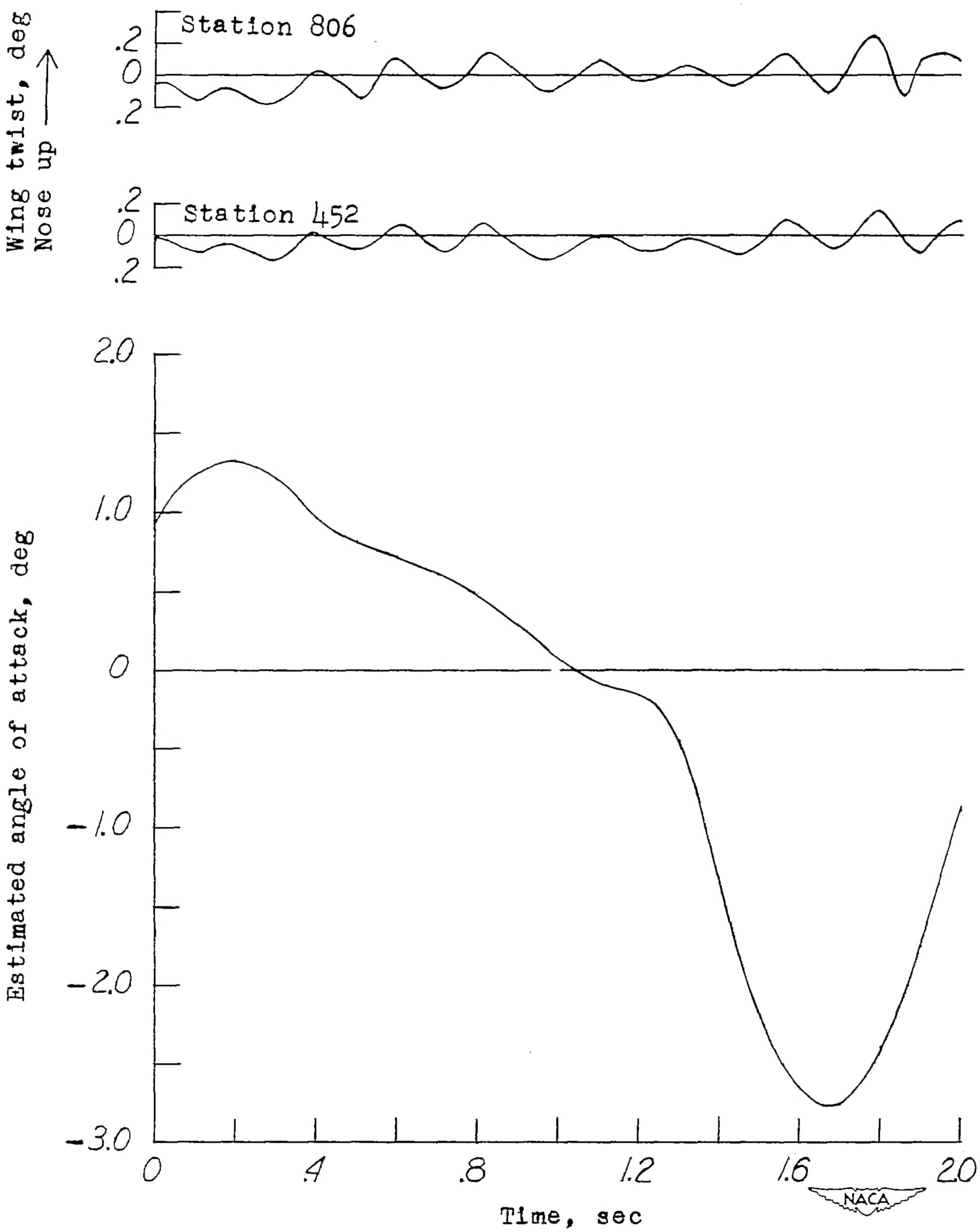


Figure 8.- Time history of wing twist and estimated angle of attack.

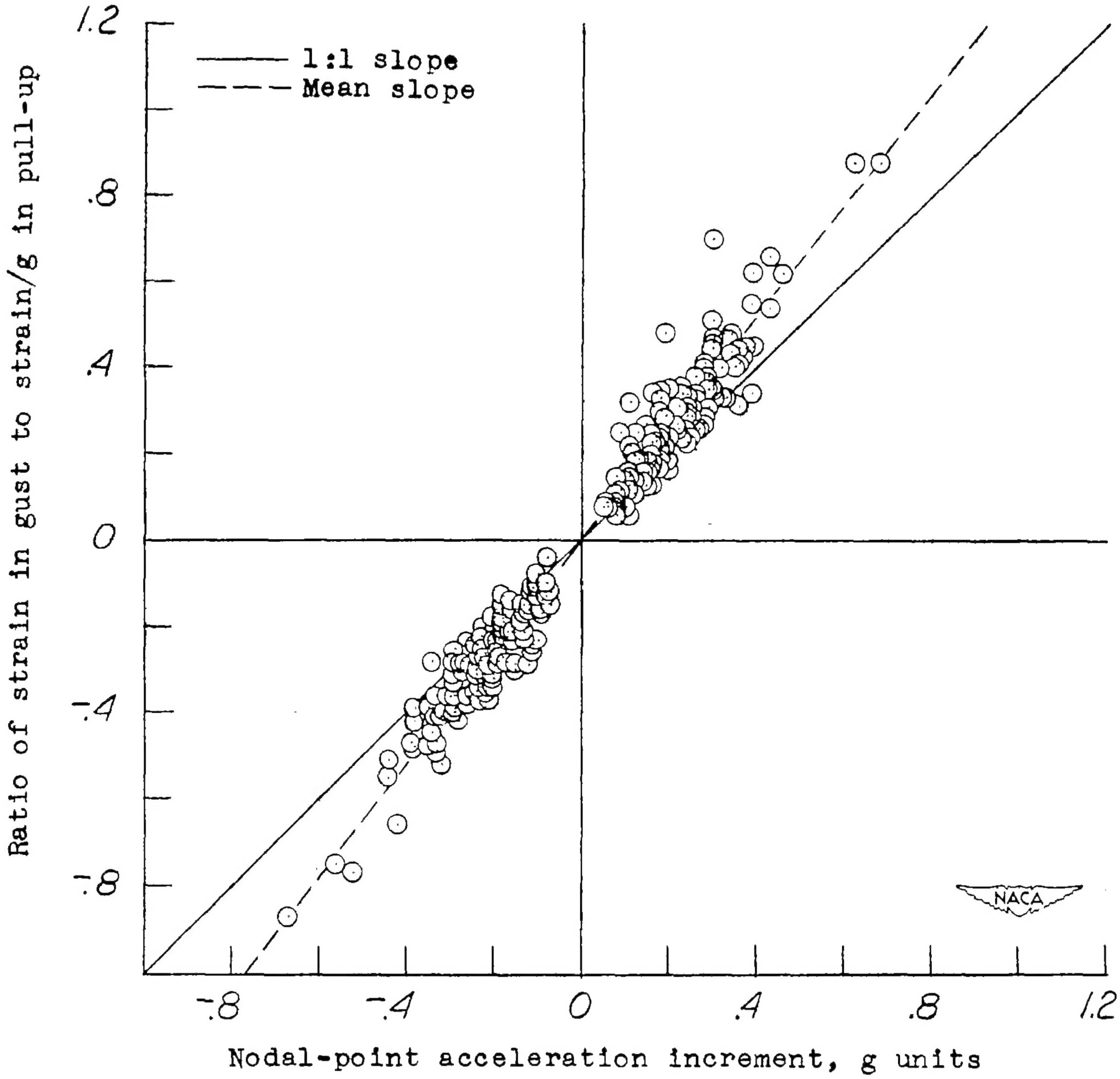


Figure 9.- Strain ratios for the wing-light high-speed condition at station 126 as a function of nodal-point acceleration.

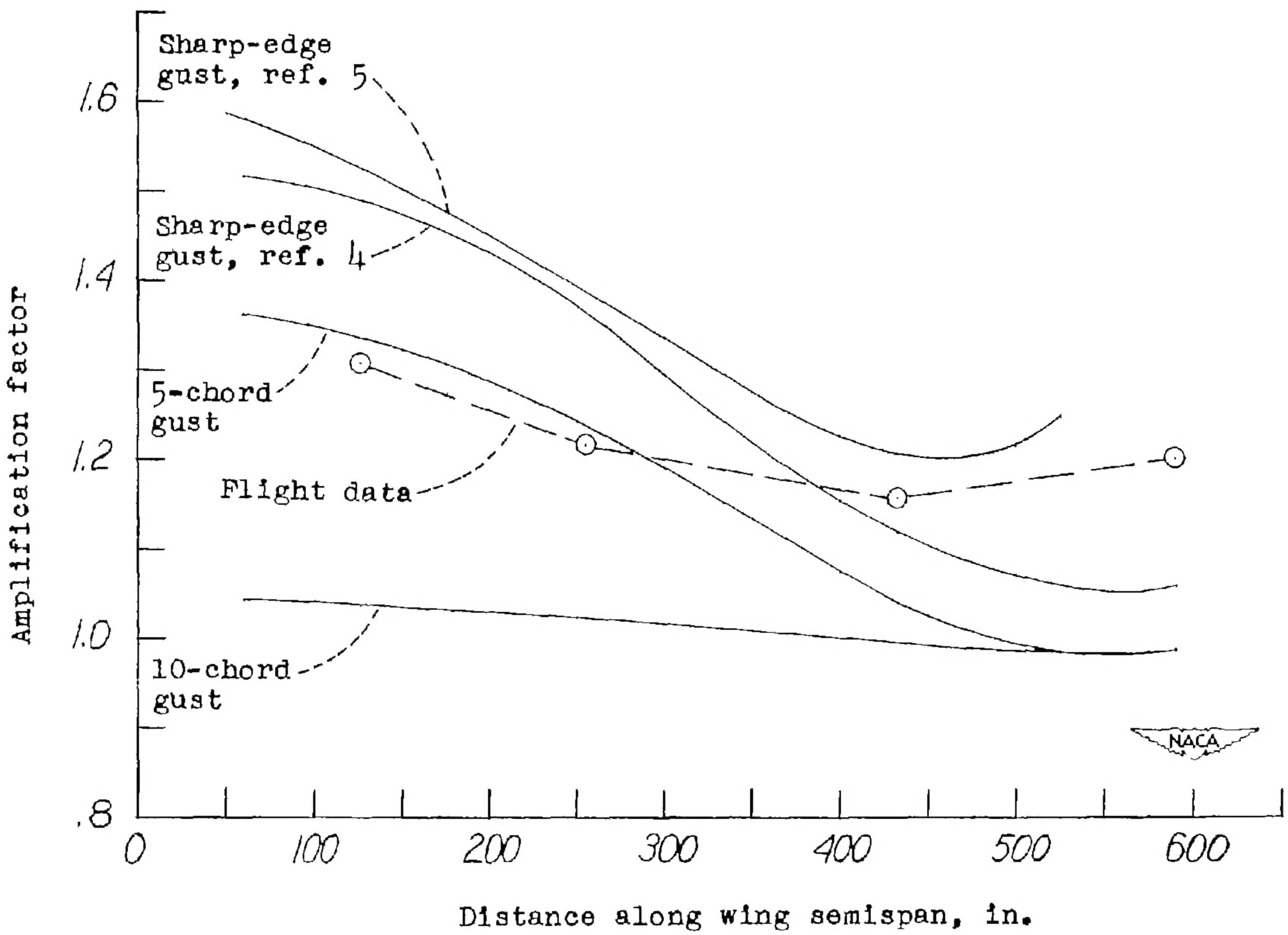


Figure 10.- Calculated variation of amplification factor along span for the wing-heavy high-speed condition.

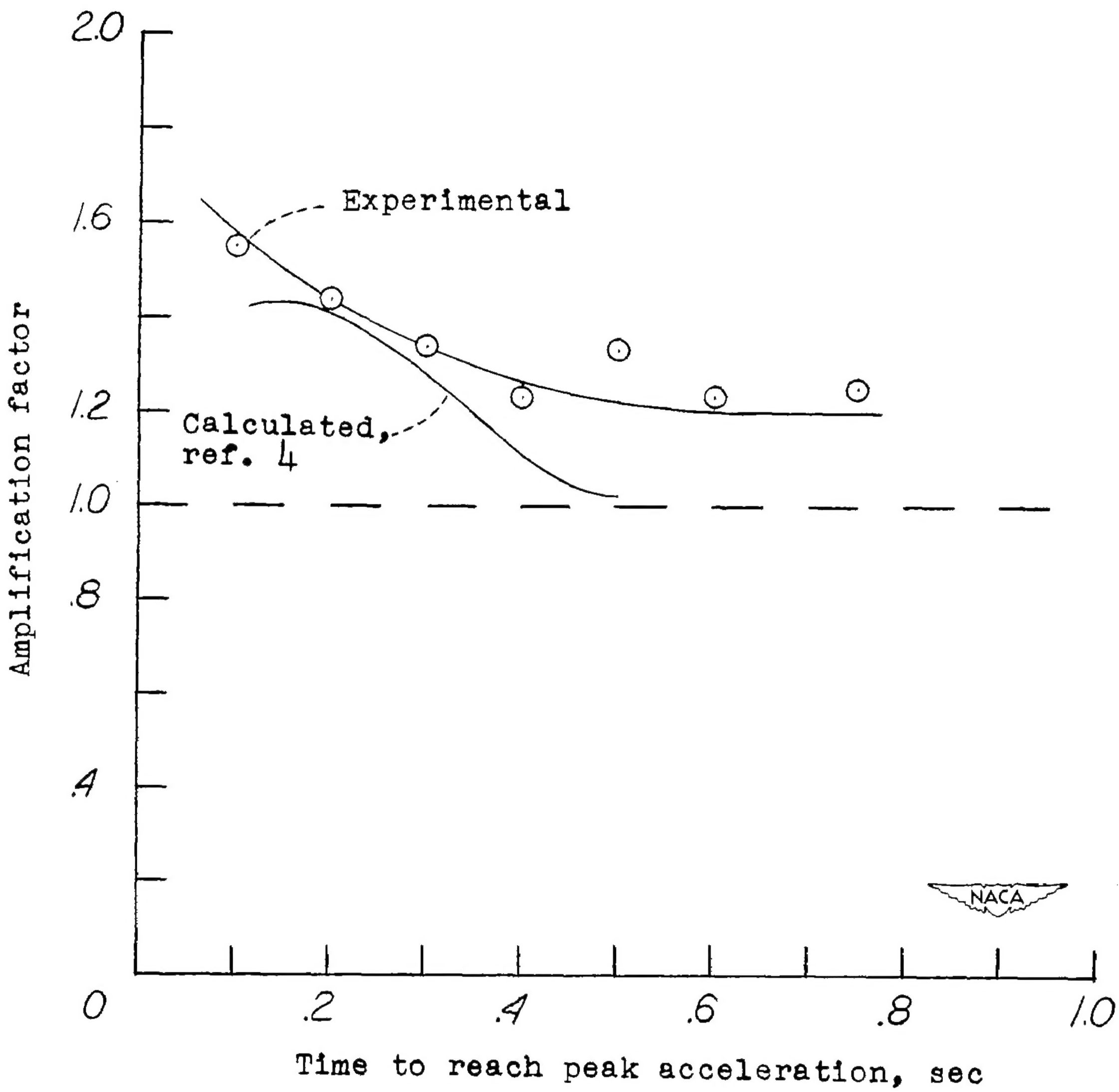


Figure 11.- Variation of amplification factor with time to reach peak acceleration for left-wing front-spar bending-strain indication at station 126. Wing-heavy high-speed condition.

NACA-Langley - 6-5-53 - 1000